CHAPTER 100

FLOATING BREAKWATER FOR RESERVOIR MARINAS

by

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ABSTRACT

The concept of multiple use of reservoirs is resulting in the construction of marinas for recreational boating requiring breakwaters that can function for a large range of water levels A typical set of design criteria is an average water depth of 20 to 25 feet, wave lengths from 5 to 60 feet (wave periods of from 1 to 4 seconds) and wave heights from ½ to 5 feet Calculations based on Bulson's results showed a pneumatic breakwater to be too expensive An extensive literature search revealed that floating structures based upon the concepts of large effective mass or moment of inertia resulting from "entrained" water, or structures which can dissipate energy might be more effective than one of the floating bag types of breakwaters Several new-types of moored floating structures which combined two or more of the concepts mentioned above were tested in a wave tank, and several of the devices appear to have merit in that they were reasonably small compared with the longest design wave length and could reduce the highest design incident wave height to less than one foot, prototype, in the lee of the breakwater

INTRODUCTION

Owing in part to the development of multiple purpose reservoir and inland lake recreation areas in recent years, the number of small craft used in these bodies of water has increased rapidly In the design of small craft harbors for the protection of boats from storms,consideration must be given to the variation of the water level This is of special importance for reservoirs because of draw-down during the summer and fall seasons It appears that mobile breakwaters might be the best solution for such a condition

Research on mobile breakwaters has been done in the past, but very few have been built One purpose of this paper is to present the conclusions reached by the authors from a literature review One can categorize mobile breakwaters into three main types 1) pneumatic and hydraulic breakwaters, 2) flexible structures, and 3) rigid floating structures

Based upon the conclusions derived from the literature review, three rigid floating breakwaters were designed, each making use of a different mechanism or combination of mechanisms of wave energy dissipation and reflection The models were designated A, B and C Later Mr J S Habel, Supervisor of Engineering of the Department of Harbors and Watercraft, State of California, and Professor J V Wehausen each suggested a concept of wave energy dissipation and reflection which resulted in the design and construction of Models

D and E

Almost no information was discovered on the maximum height and period of waves that are considered to be acceptable within a small craft marina The Task Committee on Small Craft Harbors of the American Society of Civil Engineers (1969) state on page 57 that in general, wave heights should be reduced to approximately ½ to 1 ft for small boat harbors Some data on maximum wave heights in which different classes of working barges and vessels can operate have been given by Glenn (1950) and Santema (1955)

The problem of mooring so as to prevent damage to boat, mooring lines or dock is extremely complex, depending upon wave heights, periods and direction, and upon the weight, shape, natural periods of the boat and upon the characteristics of its moorings A theoretical study was made by Raichlen (1968) for the simplified case of the surging motion of several classes of small boats (ranging from 2 to 8 tons - 20 to 40 ft in length) subjected to uniform periodic standing waves with crests normal to the longitudinal axis of the moored boats, with two bow lines and two stern lines The restoring force versus displacement of the moorings were non-linear, as is apparently the normal case A detailed analyses was made for one of the boats (Harbor Boat No 3), which had a length of 26 ft , beam of 9 ft -2 in , maximum draft of 2 ft -4 in and an approximate displacement (unloaded) of 5200 lbs Details of the mooring configuration and mooring line characteristics were also presented Measurements of the period of free oscillation of surge for three mooring line conditions (zero slack, 4 in and 8 in slack) for several different initial displacements were made and compared with theory The comparisons, shown in Fig 1, are quite good

Some of the complexities of the problem can be seen from Fig 2 which compares the maximum motion (in one direction only) of the boat as a function of wave period and the forcing function ζ for taut mooring lines and for 8 in slack ζ is a rather complicated function, and Raichlen describes it as the maximum with respect to time of the water particle velocity averaged over the displaced volume of the moored body All other things being equal, ζ is directly proportional to the standing wave emplitude It is evident that a boat moored with slack lines at one tide stage may have taut lines at another stage of the tide, so that its response will vary with tide stage, all other conditions being equal

Two other examples have been chosen from Raichlen's report, and are shown in Fig 3 The maximum positive displacement from rest is shown as a function of wave period and ζ for two boats, one of 3700 lbs with a length of 22 ft -5 in , and the other of 17,000 lbs and a length of 38 ft First, it appears peculiar that the smaller boat should have larger "natural periods" than the larger boat The reason for this was that the mooring lines of the larger boat were much stiffer compared with its weight than was the case for the smaller boat This emphasizes again that the moorings are extremely important to the problem and there can be no simple wave height criteria for a harbor

PREVIOUS WORK

Pneumatic and Hydraulic Breakwaters

An artificial surface current can be produced by air bubbles released from a comprised air manifold on the sea bed, or by means of horizontal water jets from a pipe floating on the water surface If the surface current is of sufficient magnitude, and is directed towards the oncoming waves, the wave lengths are reduced and their heights increased until instability occurs, and the waves either breaks or are reflected

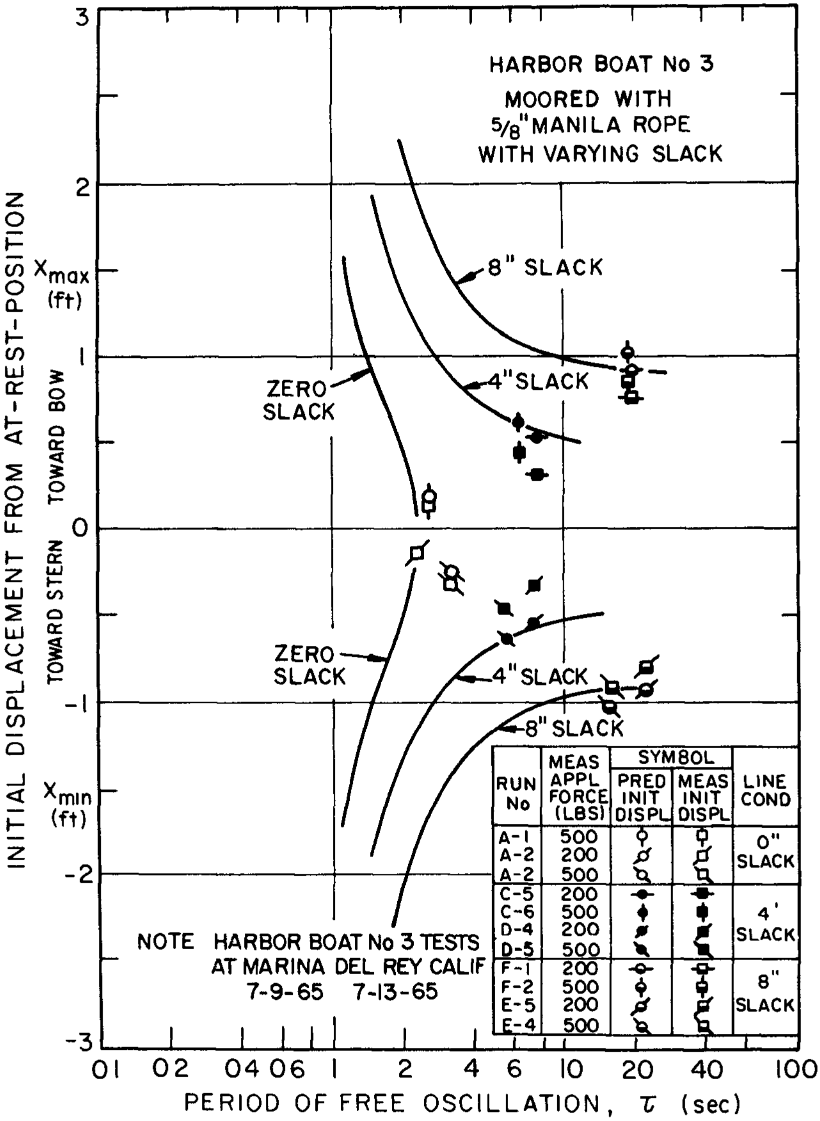


FIG 1 MEASURED AND PREDICTED PERIODS OF FREE OSCILLATION HARBOR BOAT No 3
(FROM RAICHLEN, 1968)

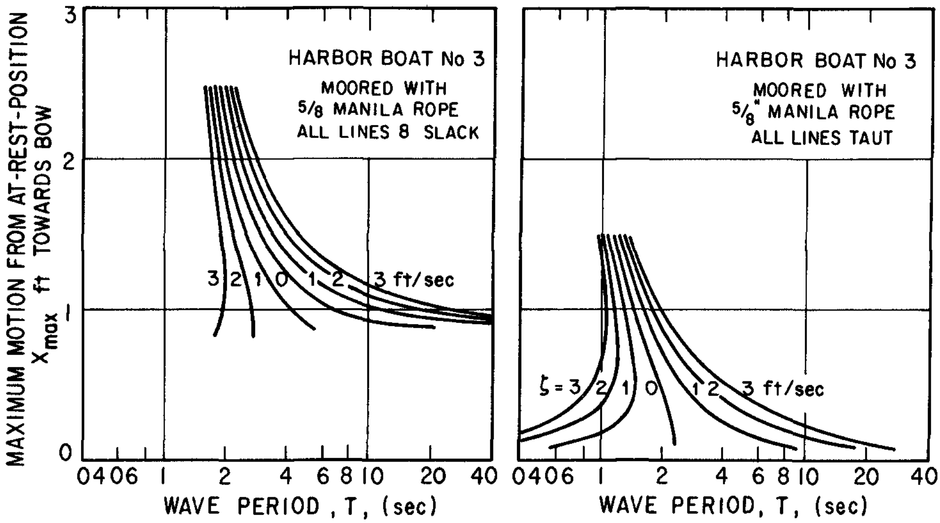


FIG 2 RESPONSE CURVES HARBOR BOAT No 3 (FROM RAICHLEN, 1968)

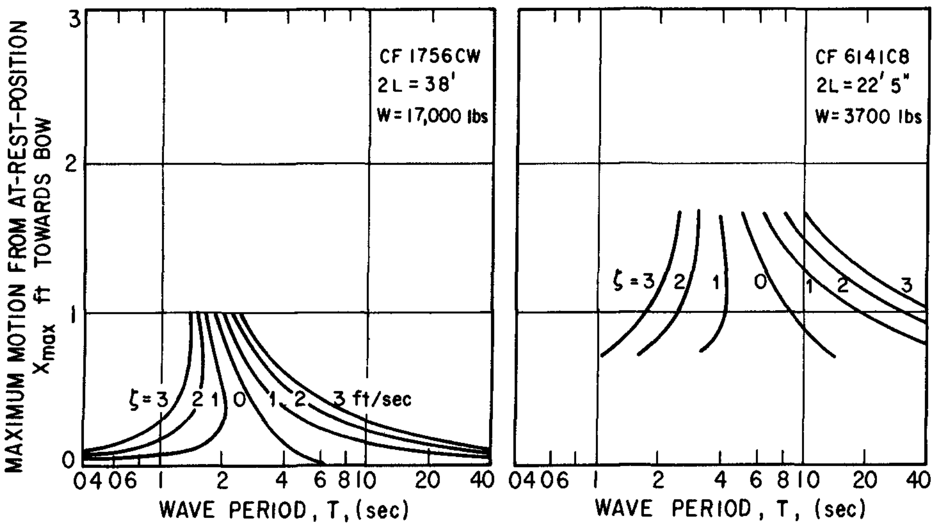


FIG 3 RESPONSE CURVES. 17,000 lb BOAT AND 3700 lb BOAT (FROM RAICHLEN, 1968)

This concept was first employed by P Brasher (1915) in 1907 It was used by the Standard Oil Company in 1915 at El Segundo, California, apparently with little success In 1936 Professor Thysse of Delft University showed that the surface currents produced by the bubbles were the main mechanism The theoretical work was continued by White (1943) and Taylor (1955) in England during 1939-1945 As a result of their work, it became possible for the first time to predict the quantity of air required to produce a given surface current as well as the speed of current required to dissipate (and/or reflect) the energy of waves of known length After World War II, a large amount of research was done in connection with this subject

Williams and Wiegel (1963) generated waves in a tank by blowing air over the water surface and subjected them to a horizontal current of water created by horizontal water jets issuing from a manifold at the water surface (hydraulic breakwater) The energy spectra of the waves were computed for conditions before and after the hydraulic breakwater was turned on It was found that the shorter, steeper wave components were attenuated to a much greater extent than were the longer wave components They concluded that although a large portion of the wave energy could get past such a breakwater, the waves in the lee of the breakwater looked considerably lower to the observer, so that the claims made for the effectiveness of this type of breakwater were probably impressions rather than reality

Both experimental and analytical studies have been carried out by Bulson (1963, 1967, 1969), who concluded

> "The experimental and theoretical studies during the past 25 years have made it possible for a reasonably accurate estimate to be made of the air quantity required to operate a bubble breakwater The quantity is astronomical and costly to supply The practical difficulties of operating a full scale system are immense It is doubtful whether any novel ideas of bubble formation and size can produce economices, and high cost is bound to be the basic feature of any apparatus of this type which is designed to combat the energy of the sea "

It was thought that perhaps a pneumatic breakwater might be a reasonable solution for the relatively short waves expected to be encountered in a reservoir Calculations were made for the following conditions water depth of 20 ft , wave lengths from 5 to 60 ft (wave periods from 1 to 4 seconds), and wave heights from ½ to 5 ft Based on Bulson's results, one can calculate the quantity of air required to suppress waves of length L, height of H, in water depth, d

$$V_m = 1\ 46 \left[\frac{gQoP}{P+d}\right]^{1/3} \qquad (1)$$

where V_m = the surface velocity of the current, feet per second

Q_o = the quantity of free air delivered by compressors,cubic feet per second per foot

P = atmospheric pressure expressed as a head of water, feet of water

In this case the air supply manifold is placed on the bottom

The current velocity V diminishes approximately linearly with depth, until it equals zero at a depth D below the surface

$$D = 0\ 32\ P \operatorname{Log}_e \left[\frac{P+d}{P}\right] \quad \text{feet} \qquad (2)$$

When the same quantity of air passes through a variety of orifice diameters and spacings, there is no significant difference in V_m, furthermore, results for a single manifold at depth d are not noticeably different from those when two or more adjacent manifolds deliver the same total quantity of air The critical current velocity at the surface to suppress completely deep water waves, V_m, is given by

$$\bar{V}_m = \frac{1}{\alpha_m}\left[\frac{\lambda g}{2\pi}\right]^{\frac{1}{2}} \tag{3}$$

where $$C^2 = gL/2\pi \quad \text{for deep water} \tag{4}$$

and $$\alpha_m^2/z = L/2\pi D \tag{5a}$$

$$z = Dg/\bar{V}_m^2 \tag{5b}$$

in which C is the wave speed in feet per second α_m can be obtained from Fig 5 of Bulson's 1969 paper Combining Eqs (1) and (3)

$$Q_{cr} = \left[\frac{P+d}{P\ g}\right]\left[\frac{gL}{2\pi}\right]^{3/2}\left[\frac{1}{1\ 46\alpha_m}\right]^3 \tag{6}$$

According to Eq (6), Q_{cr} is independent of wave height, but experiments show that when waves are neither truly sinusoidal nor of infinitesimal height, the quantity of air necessary to produce complete damping can exceed Q_{cr} It has been suggested by Bulson that Q_{max} can be represented by linear relationship between Q_{max}/Q_{cr} and the wave steepness, H/L

$$Q_{max}/Q_{cr} = 0\ 6 + (20\ H/L)$$

Suppose one wishes to determine the quantity of air required to suppress waves 60 ft long, 5 ft high in a water depth of 20 ft From Eq (2), $D = 0\ 32 \times 33 \times \text{Log}_e\ (63/33) = 6\ 83$ ft Also, $\frac{\alpha_m^2}{z} = 60 / (2\pi \times 6\ 83) = 1\ 4$, and from Fig 5 of Bulson's paper, $\alpha_m = 3\ 05$ Substitution in Eq (6) gives $Q_{cr} = (33 + 20)/(33 \times 32\ 2) \times (g \times 60 / 2\pi)^{3/2} \times (1/1\ 46 \times 3\ 05)^3 = 3\ 59$ cfs/ft Finally, $Q_{max}/Q_{cr} = 0\ 6 + (20\ H/L) = 2\ 27$, and $Q_{max} = 8\ 15$ cfs/ft
Therefore, the quantity of free air required is 8 15 cfs per ft This represents an air power at the pipe of 26 horsepower per foot Thus, a 300 yard long breakwater would require a total of 23,400 Hp The operation alone is very costly, even if installation costs were not considered

Flexible Breakwaters

In general a floating structure of relatively light weight will only be able to reflect a small amount of wave energy If, however, the structure has sufficient length, a larger amount of wave damping and wave reflection will occur

Model tests performed by Wiegel et al (1959), showed that floating sheets of plastic material will have a wave damping effect if the length of the plastic sheets, λ, is equal to many times the wave length, L For a value of $\lambda/L = 5$, the wave height behind the structure appeared to be equal to $H_T = 0\ 8\ H_I$, for $\lambda/L = 10$, $H_T = 0\ 4$ to $0\ 5\ H_I$, and for $\lambda/L = 20$, $H_T = 0\ 2\ H_I$ From a similar series of tests it appears that with a layer of plywood a wave reduction up to 50% could be obtained with $\lambda/L = 2$ to 3 Other studies were made of the wave damping properties of waterfilled bags, ("hovering breakwater") floating in the water with their top at the water surface The dimensions of the bags were 10' x 10' x 4" The results showed that within the range of L/λ from 0 5 to 0 8, the ratio of the wave height in the lee of the "hovering breakwater" to that of the incident wave (H_T/H_I) was approximately equal to the ratio L/λ This means that an effective damping requires a relatively wide structure

Tests made with prototype waves in San Francisco Bay, with a hovering breakwater 20' x 24' x 4' deep in water 7' deep (below MLLW) by Wiegel, Shen and Cumming (1962) showed that H_T/H_I was one-half of the value obtained in the laboratory for the same value of L/λ, using the "significant wave length" computed from the measured "zero upcrossing period' of about 1 7 seconds The reason why the "prototype" was more effective than the "model" was not determined

Other extensive experiments were made by Ripken (1960) These experiments deal with the wave damping properties of cylindrical bags, filled with air or liquid, which are placed just below the water surface with their longitudinal axis parallel to the direction of wave propagation It was found that a satisfactory attenuation requires a bag length of about 1 5 to 2 times the wave length A diameter of 20% of the water depth was recommended for the cylindrical bags, although the influence of the relative depth appeared to be small A filling of about 95% seems to be the most effective filling percentage for the bags Use of fluids in the bag of a greater viscosity than water did not substantially increase the amount of wave attenuation Ripken stated that the wave attenuation provided by water filled bags was associated with a progressive pressure wave in the bag This pressure wave was found to be slightly out of phase with the wave motion As a consequence of this, the material used for the bags must be strong

Other studies were carried out by Ripken (1960) for two different types of wave absorbers a blanket and a shallow moored floating structure Ripken concluded

> The degree of attenuation achieved increases as the ratio of wave length to blanket length decreases and as the ratio of blanket thickness to water depth increases 'The blanket thickness should be of the order of 15 percent or more of the water depth For a thin blanket the length should be several times as long as the wave length A multiple of about three or more is indicated depending on the attenuation desired "

A similar conclusion was reached in regard to the wave trap, a considerable length is needed to damp the oncoming waves

An experimental study of fascine mattress composed of willow twigs and reeds has been made by Vinje (1966) It appeared that the wave attenuation was nearly 45-50% when the ratio of the length of mattress to the length of wave was larger than 1

There are some other studies which have been made, and the general conclusion appears to be that the length of breakwater in the direction of wave propagation should be much larger than the wave length

Floating Rigid Structures

Floating structures have three modes of oscillation due to the restoring force of gravity rolling, pitching, and heaving A moored floating structure has three additional modes of oscillation owing to the restoring force of the moorings A floating structure which is to reflect wave energy must have the requisite long natural periods in each of these three modes of oscillation compared with the wave periods To obtain a long natural period, it is necessary to combine a large mass with small "elasticity " In a floating structure the 'elasticity" is represented by its change in buoyancy as it heaves, rolls, and pitches A solution of this problem is the enclosure of a large mass of water within a relatively light enclosing structure in such a way that the restoring force was reduced to a minimum This was the principle of Bombardon floating breakwater designed for and used in the Normandy invasion of World War II (Lochner, Faber and Penney (1948) In the official report on the operation of Bombardon floating breakwater the following statement was made

> "A full scale breakwater, assembled off the Dorset coast in April 1944, successfully withstood an on-shore gale of force 7 (30 m p h) with gusts up to force 8 (39 m p h) "
>
> "Both breakwaters were moored in 11-13 fathoms, giving sufficient depth inshore for Liberty ships to anchor In this depth they reduced the height of the waves by the measured amount of 50%, which represents a 75% reduction in wave energy These measurements were carefully made at the British harbour on the 16th June, 1944 with a wind blowing force 5-6 Unloading operations and small boat work were going on inside the breakwater at that time which would not have been possible outside the breakwater "

The requirement of large mass may be usefully replaced by large moment of inertia of mass in the development of floating breakwaters This concept has been applied by Brebner and Ofuya (1969) in developing the "A" frame breakwater The "A" Frame breakwater consists essentially of a central rigid curtain of wood, and two aluminum cylinders symmetrically located and rigidly connected to the curtain at intervals The mass radius of gyration of the structure about a lateral axis through its center of gravity (axis parallel to wave crest) may be varied by altering the cylinder spacing Laboratory experiments showed that an effective floating breakwater system can be developed in which a large moment of inertia of mass is the dominant factor rather than the mass The reduction of wave heights is effected through the processes of wave reflection, dissipation, and wave interference The best wave damping was obtained when the distance between the cylinders was nearly equal to the wave length

The third concept is that of a perforated breakwater which was originally developed by Jarlan (1965) This study is concerned with the application of that breakwater as a mobile system and for possible operation in the floating-moored or fixed to the bottom A recent study has been done by Marks (1967) who states

> " The dynamic processes that result from the incidence of waves on the perforated breakwater can best be visualized by considering [Fig 3] * As the wave impinges on the porous front wall, part of its energy is reflected and the remainder passes through the perforations The potential energy in the wave is converted to kinetic energy in the form of a jet, upon passage through the perforation, which then bends to be partially dissipated by viscosity in the channel and partially by turbulence in the fluid chamber behind the perforated wall As the water in the fluid chamber flows back out of the holes, it encounters the next oncoming wave and partial energy destruction is accomplished even before that wave reaches the breakwater If the walls were not perforated (e g a caisson), total reflection would occur on the face of the wall with resultant high impact forces and scouring on the base, if it is

fixed to the bottom If the breakwater were floating and anchored, part of the incident wave force would be transmitted to the mooring cables and part would be directed to oscillating the breakwater thus inducing it to make waves on the shoreward side In the case of the perforated breakwater, that part of the incident wave energy which is dissipated internally in the form of heat and eddies is not available for such deleterious activity Hence, it is expected that less force would be felt in the mooring lines, and/or that smaller waves would be produced shoreward of the breakwater "

' It is clear that wave attenuation is most effective at low periods and least at high periods The perforated unit is better up to about 9 seconds of wave period and worse beyond compared with caisson type "

"The breakwater geometry specifying 4-foot diameter holes, 4-foot wall thickness, and 40 feet between front and back wall was found to be most effective, as predicted by theory The mooring lines in the perforated breakwater experienced less force by about a factor of 2 compared with caisson type Wave reduction by the solid floating-breakwater varied from about 0 2 to 0 6 For the perforated floating breakwater, wave reduction varied from about 0 2 to 0 8 As expected, the perforated breakwater was far effective in reducing wave height for shorter waves (0 1 to 0 3) than for longer waves (0 6 to 0 7) "

NEW MODEL FLOATING BREAKWATERS

Introduction

It was decided to design three types of rigid structure breakwaters for laboratory testing, combining the principle of the use of a large entrained moment of inertia with the principle of partially absorbing the wave energy by a perforated wall or by a sloping board The three types have been designated Type A, B, and C

The experiments were performed in a 106 ft long by 1 ft wide by 3 ft deep wave channel The water depth in the wave channel was set at 25 in , corresponding to a "prototype" depth of 25 ft The floating breakwater model was placed about seventy feet from the wave generator An energy absorbing beach was located at the other end of the channel Wave measurements were obtained at a position about 15 ft 'seaward" of the floating breakwater model and at a location about 8 ft to the "lee" of the model, using parallel wire resistance wave gages (Wiegel, 1956)

Two wave heights were used for each wave length tested, one low and one high, to check approximately the effect of wave steepness (also, called the wave slope) on the phenomenon The wave length, L, is related to the wave period, T, and water depth, d, by the equation

$$L = \frac{gT^2}{2\pi} \tanh \frac{2\pi d}{L} \qquad (7)$$

in which g is the acceleration of gravity For the water depth and wave periods tested, this equation could be approximated by

$$L \approx gT^2/2\pi \qquad (8)$$

A portion of the wave energy was transmitted to the lee of each breakwater as a train of waves, a part of the energy was dissipated, and a part of the energy was reflected as a train of waves Little wave energy was reflected by Model A breakwater, while Models B, C, D and E reflected a considerable amount of wave energy No attempt was made to measure the amount of wave energy reflected

The most important parameter of the study is the transmission coefficient, defined as

$$\text{Wave Transmission Coefficient} = \frac{\text{Transmitted Wave Height}}{\text{Incident Wave Height}} = \frac{H_T}{H_I}$$

A typical example of the record of both the incident and transmitted wave heights is shown in Fig 4 It can be seen that the reflected waves interfered with the incident waves in a complex manner Reported values of the wave transmission coefficient were based on the largest transmitted wave height and the average incident wave height

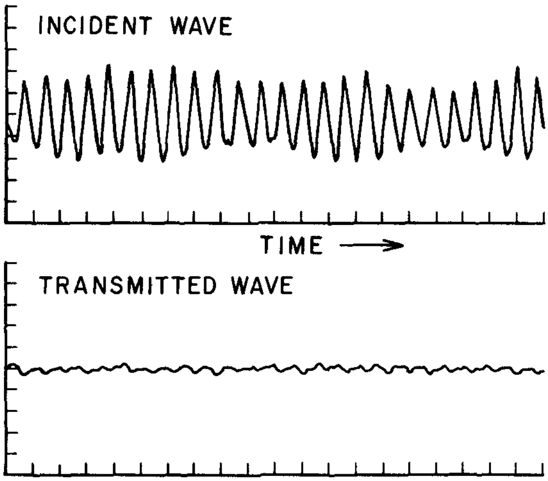


FIG 4 RECORD OF INCIDENT WAVE AND TRANSMITTED WAVE

One important factor that was not studied at this stage was the mooring line system and the mooring forces The mooring line system forms an important feature of a floating breakwater since breakwater performance depends on the type of restraints imposed on its motion by the mooring lines Three additional natural periods result from the mooring lines yaw, sway and surge Further studies must be made on the mooring system Different types of floating breakwaters moorings need to be studied to find out the best mooring system

Model A

The basic concept of this design was the dissipation of wave energy by waves breaking on a sloping board "beach"

Model A, shown in Fig 5, consisted of a sloping board "beach," with the seaward end attached to a rectangular air chamber (pontoon) which provided buoyancy The "lee side" of the sloping board was connected to a vertical wall (14" high) by steel frames A "lee side" floating box (pontoon) was connected to the vertical wall by a steel frame The total length, λ, of this model was 43 5 in (i e , 43 5 ft , "prototype" as the ratio between the model and the contemplated breakwater for use in reservoirs is 1 12)

In order to check the effect of the height of the vertical wall on the wave transmission coefficient, the model was modified by increasing the height of the vertical wall to 22 in (22 ft , prototype), with about 19 in (19 ft , prototype) of it being submerged

It was found that when the incident waves moved over the sloping board "beach," they started to break as if they were moving over a sand beach The small amplitude waves broke completely on the board The large amplitude waves did not break completely on the board "beach" owing to the limited length of the board For waves which were about as long as the dimension λ of the breakwater, or shorter, a substantial amount of wave energy was dissipated in this breaking process The top of the board 'beach" was designed to have a saw tooth shape The large amplitude waves partially broke on the board "beach,' then ran over the top of the board, dropping through the space into the water on the lee side of the "beach ' No water went over the top of the vertical wall Considerable air entrainment and mixing occurred during the process This periodic impact of the wave run-up dropping on the water surface eventually created a pressure fluctuation in the water under the board "beach," and in front of the vertical wall The water moved up and down in this region This resulted in a pressure fluctuation in the region between the bottom of the vertical wall and the bottom of the tank, which in turn caused a heaving motion of the water surface in the section between the vertical wall and the lee side pontoon It appeared that the distance between the vertical wall and the lee side pontoon would be important, but lack of time prevented a study of various spacings

A further observation was made by permitting the model drift (e g , the mooring lines were removed from the model) in the waves It was found that Model A drifted much more slowly than Model B It was believed that the slow rate of drift indicated there would not be too great a problem in mooring the structure

The results of the wave transmission coefficient vs the ratio of wave length to breakwater length (L/λ), and vs the wave length (given in "prototype' scale) are shown in Fig 6 The results show an irregular curve In the range of wave lengths from 30 ft to 55 ft (prototype), the steep waves (wave slope = 0 055-0 075) had a higher transmission coefficient than did the waves of relatively small steepness (slope = 0 022-0 030) The term wave steepness refers to the ratio of the incident wave height to the wave length (H_I/L) The two curves crossed at a wave length of about 60 ft , and in the range of wave lengths from 65 ft to 90 ft , the relationship was opposite to that for the smaller wave lengths

When the model was modified with the 22 in (22 ft , prototype) deep vertical wall, there was less difference in the transmission coefficients for the relatively flat waves than the steep wave There was about a 10 percent improvement in the wave transmission coefficient for the range of wave lengths between 60 ft and 80 ft (prototype)

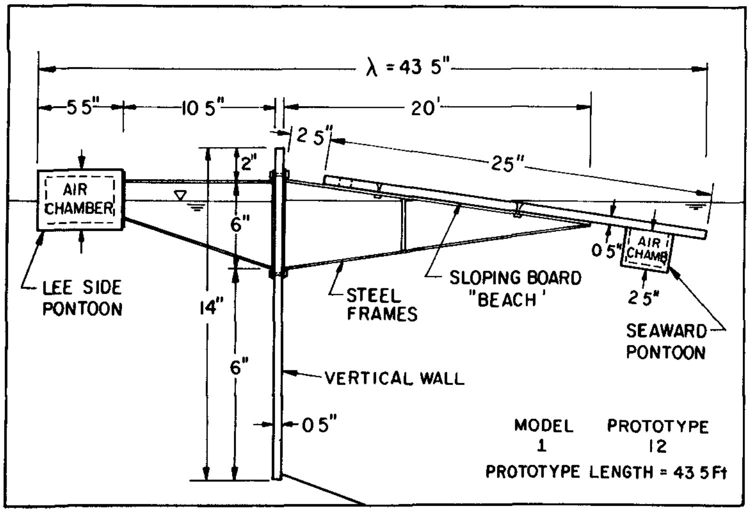


FIG 5 FLOATING BREAKWATER "TYPE A"

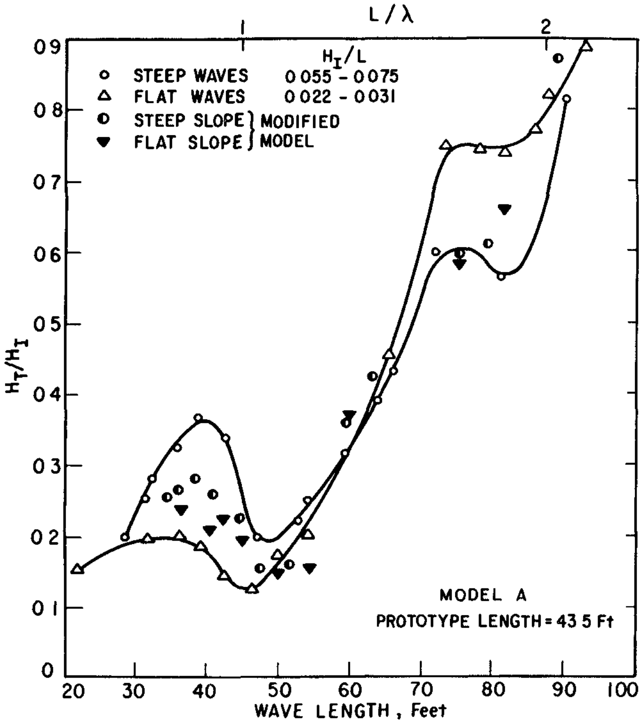


FIG 6 TRANSMISSION COEFFICIENT vs WAVE LENGTH (ALSO L/λ)

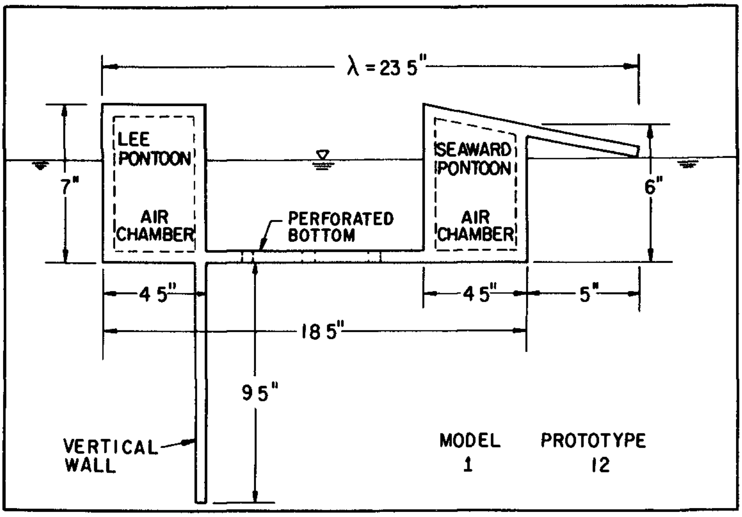


FIG 7 FLOATING BREAKWATER "TYPE B"

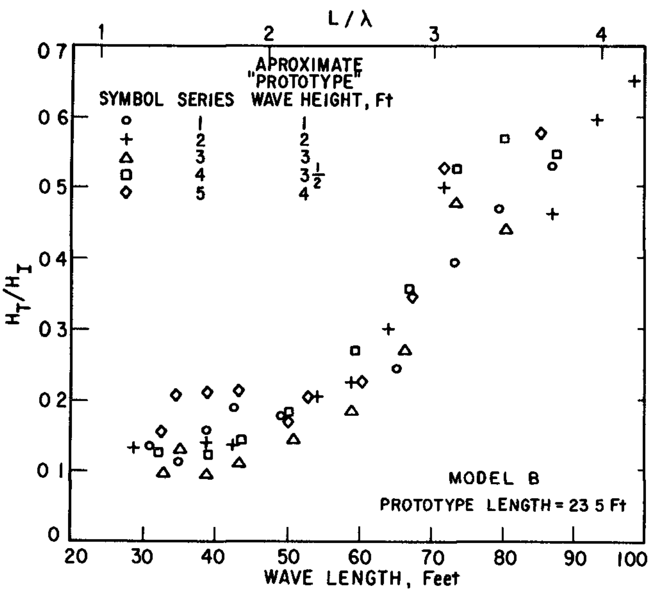


FIG 8 TRANSMISSION COEFFICIENT vs WAVE LENGTH (ALSO L/λ)

Model B

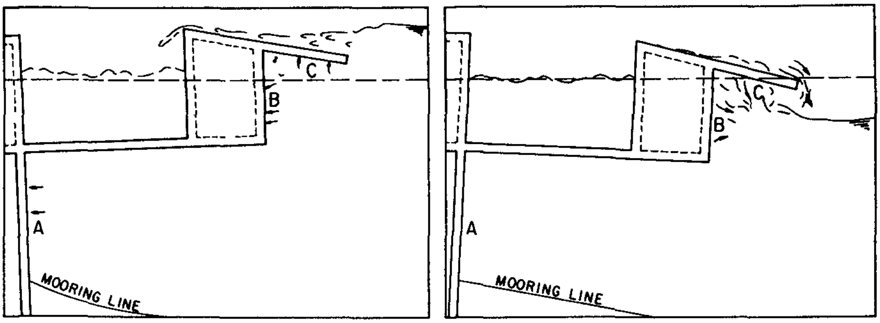
Floating breakwater Model B, shown in Fig 7, consisted of two pontoons separated by a perforated bottom The length, λ, of the structure is 18 5 in (18 5 ft , prototype), with an additional 5 in (5 ft , prototype) of sloping "beach' extending seaward above the water surface for a total length of 23 5 in (23 5 ft , prototype) A vertical barrier was attached below the lee side of the perforated section The pontoon on the lee side had a rectangular cross section The pontoon on the weather side has unequal vertical sides, with a sloping top extending outwards a distance of 5 in (5 ft , prototype) towards the weather side

The results of the wave transmission coefficient vs wave length and vs L/λ are shown in Fig 8 for five series of runs, each with a different wave height For wave lengths less than 60 ft , prototype, (L/λ less than 2 7), the transmission coefficient is less than about 0 20 Considering the expected range of wave lengths in a reservoir, this is probably a satisfactory attenuation For wave lengths between 65 ft and 80 ft (prototype), the transmission coefficient rises rapidly from about 0 3 to 0 5 For wave lengths of about 90 ft (L/λ of 3 8), the transmission coefficient rises to 0 60-0 65 Under the latter circumstances, a substantial portion of the wave energy is transmitted past the floating breakwater

It appeared that more than half of the energy of the incident waves was reflected by the breakwater as a wave train, with an "apparent higher frequency" than the frequency of the incident waves The breaking up of the oncoming waves into a series of smaller reflecting waves appeared to result in smaller forces acting on the mooring system The action of the water and the structure is shown schematically in Fig 9 In Fig 9 the oncoming wave crest is shown striking surfaces A, B and C, it then reflects at different times in the form of a series of reflecting waves with a smaller amplitude compared with the incident waves, and with different phases

Owing to the vertical barrier and the overall geometric arrangements, this floating breakwater had a rather large moment of inertia with respect to rolling motion Also, the center 'water channel" with the perforated bottom worked as a damping device, in some ways similar to an antirolling tank on a ship For oncoming waves with large amplitude, the crest washed over the sloping top of the weather side pontoon, flowed into the center channel and then flowed through the perforated bottom Part of the energy apparently was dissipated by water rolling over the top of the slope and by the eddies that formed in the water channel Some air trapped under the surface of the extended portion of the sloping top of the seaward pontoon was compressed, and mixed with the water This process was too complicated for analysis, but it appeared to be a good mechanism for dissipating some of the wave energy

The tension in the mooring line consisted in general of two components, one caused by the rolling motion of the breakwater, and one caused by the wave crests striking the structure However, the model was designed so that the two components would not cause maximum forces in the mooring line at the same time Since the axis of rolling of the system is above the mooring point, when the incident waves strike on the system, the rolling motion of the body tended to release the tension in the mooring line When the incident wave troughs reached the floating breakwater, the tension in the mooring line was caused only by the rolling motion



(a) WAVE CREST AT BREAKWATER (b) WAVE TROUGH AT BREAKWATER

FIG 9 SKETCH SHOWING WAVE ACTION ON MOOEL B

Model C

Model C (Fig 10) is a type of perforated breakwater the purpose of the perforated wall being to decrease the direct striking force by decreasing the reflecting area and to dissipate wave energy by the flow of water through the holes The "water chamber" has two perforated walls The back will extends downward as a vertical barrier to provide sufficient moment of inertia of added mass The air chamber (pontoon) serves as a walkway along the breakwater During the model test, ballast was used to obtain proper balance of the structure This model was the shortest of all five models, being only 14 in (λ = 14 ft , prototype) long

Values of H_T/H_I vs wave length and vs L λ are shown in Fig 11 For wave lengths up to about 40 ft , the result appears to be reasonably satisfactory The curve of the wave transmission coefficient vs wave length (and vs L/λ) has a rather steep slope

The expected amount of energy dissipation did not occur The rest of the energy was either reflected or transmitted past the breakwater either through the motion of the breakwater which acted as a wave generator, or by wave energy passing under the structure

Model D

The side and top views of Model D are shown in Fig 12 The platform, 32 in (λ = 32 ft prototype) in length, was ballasted sufficiently to cause it to be immersed with its bottom 6 in (6 ft prototype) beneath the water surface A series of gates were suspended vertically upwards by their own buoyancy Each gate was connected to the platform by a rubber sheet hinge A string was used to restrain the motion of the gates to only one side from the vertical The gates were designed so that the rolling motion of each row of gates could move in only one direction in an alternative manner The model was carefully ballasted so that each gate emerged 0 5 in (0 5 ft , prototype) above the water surface It was designed so that any water current could bypass the series of gates with a rather small striking force, and to dissipate the energy through turbulence The restrained motion of the gates may interrupt the orbital motion of the waves and energy dissipation occurs The motions of the water current and the gates are shown in Fig 13

The experimental results are shown in Fig 14 The high wave transmission coefficients are due to the following two reasons First, the joint between the gates and the platform was a one-inch wide (model dimension) rubber sheet instead of a simple hinge Because of the inflexibility, the motion of the gates was not confined to a simple rolling motion, but also had a parallel displacement which regenerated the wave and transmitted the wave energy to the lee of the breakwater In addition, the simple flat platform provided a smaller moment of inertia (largely due to added mass) than a structure with a vertical barrier

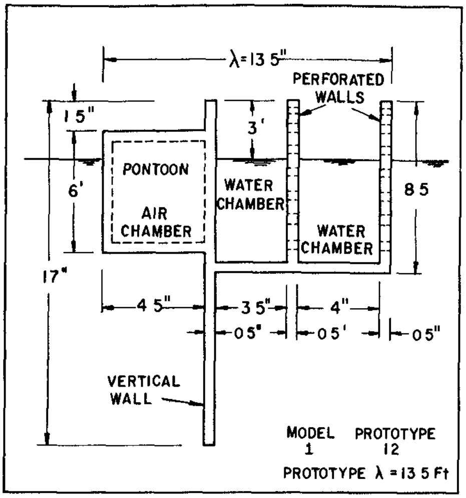


FIG 10 FLOATING BREAKWATER TYPE "C"

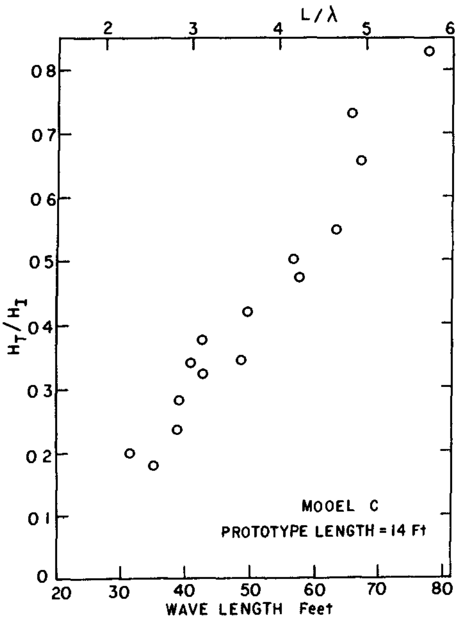


FIG 11 TRANSMISSION COEFFICIENT vs WAVE LENGTH (ALSO L/λ)

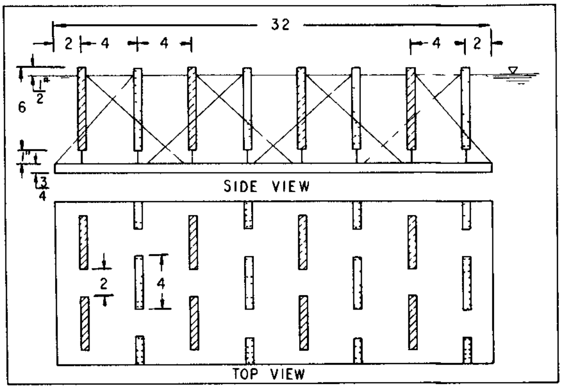


FIG 12 FLOATING BREAKWATER TYPE D

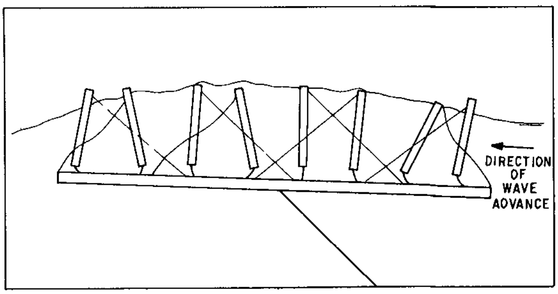


FIG 13 WAVE PASSING BREAKWATER TYPE D

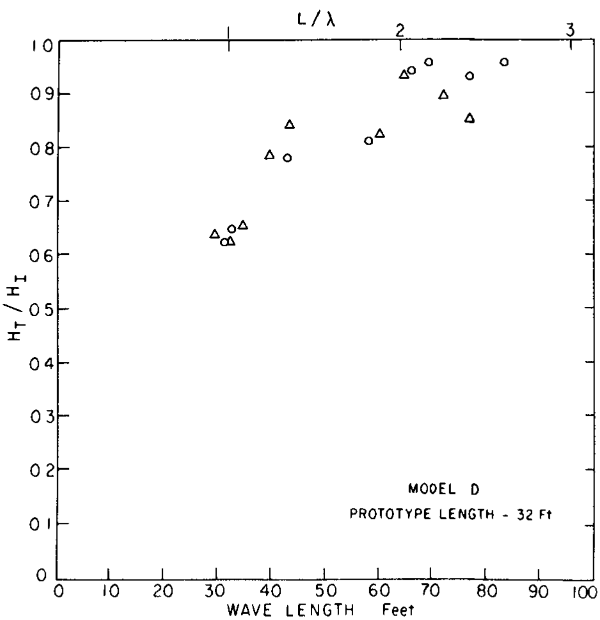


FIG 14 TRANSMISSION COEFFICIENT vs WAVE LENGTH (ALSO L / λ)

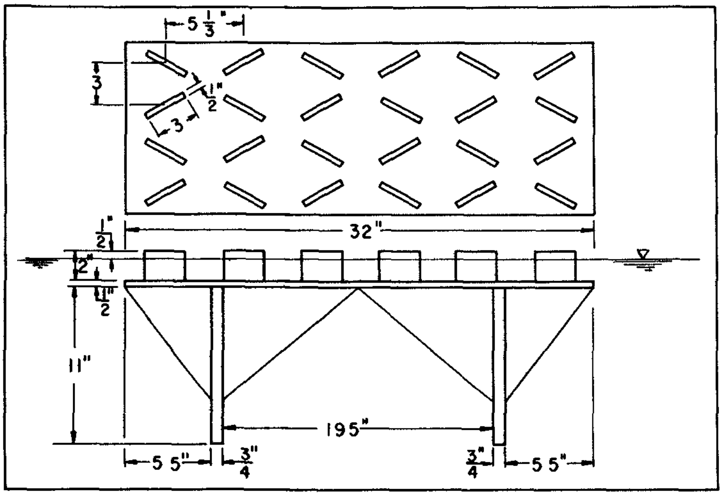


FIG 15 FLOATING BREAKWATER TYPE 'E'

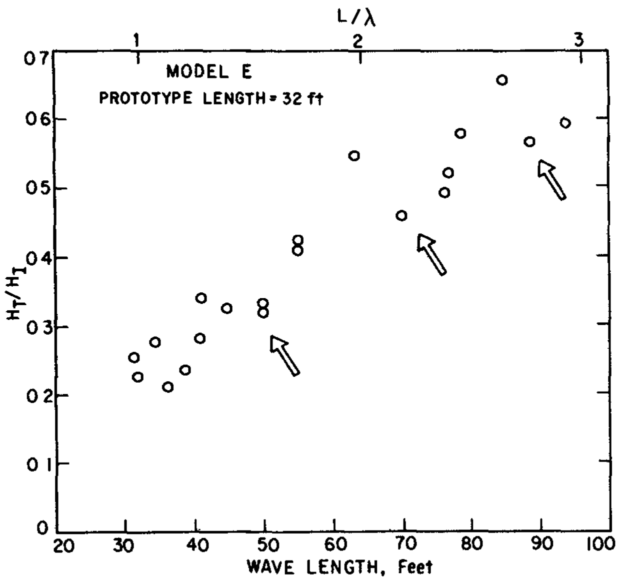


FIG 16 TRANSMISSION COEFFICIENT vs WAVE LENGTH (ALSO L/λ)

Model E

In order to avoid the transmission of energy through the gates, another model was adopted, based upon the concept of a fixed energy dissipator similar to those used at the foot of a spillway, rather than using the flapping gates The vertical walls and the platform formed a π shape (Fig 15), which provided a large moment of inertia (largely due to added mass), and minimized the transmission of wave energy under the platform The length, λ, of the structure was 32 ft , prototype The vertical sections mounted on the top side of the horizontal submerged platform consisted of six rows of blocks Each block was set at an angle of 30 degrees to the direction of wave propagation in an alternating pattern

Energy dissipation occurred as the waves washed through the maze of vertical blocks, and formed eddies and turbulence It was observed that the waves collided with the platform This collision may have been caused by the combination of the motion of the platform and the wave motion This occurred for wave lengths of about 50 ft , 70 ft , and 90 ft prototype The impact of this wave collision apparently resulted in the dissipation of some of the wave energy, this can be seen in the plot of wave transmission coefficient vs the wave length (and L/λ) for wave lengths of 50 ft , 70 ft , and 90 ft (see arrows in Fig 16)

As can be seen in Fig 16 the transmission coefficient was about 0 45 for a wave length of about 60 ft , prototype

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